IN PURSUIT OF IMPROVING AIRBURST AND GROUND DAMAGE PREDICTIONS: *RECENT ADVANCES IN MULTI-BODY AERODYNAMIC TESTING AND COMPUTATIONAL TOOLS VALIDATION*

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Abstract: An airburst from a large asteroid during entry can cause significant ground damage. The damage depends on the energy and the altitude of airburst. Breakup of asteroids into fragments and their lateral spread have been observed. Modeling the underlying physics of fragmented bodies interacting at hypersonic speeds and the spread of fragments is needed for a true predictive capability. Current models use heuristic arguments and assumptions such as “pancaking” or point source explosive energy release at pre-determined altitude or an assumed fragmentation spread rate to predict airburst damage. A multi-year collaboration between German Aerospace Center (DLR) and NASA has been established to develop validated computational tools to address the above challenge.

Classical Models for Asteroid Fragment Spreading

- Meteoroid entry and break-up models, such as the FCM code [1] employed by NASA, must account for dispersal of fragments in order to produce realistic energy deposition profiles
- These are typified by those of Passey and Melosh [2], and Hills and Goda [3], which include an empirical parameter, C_{disp}.

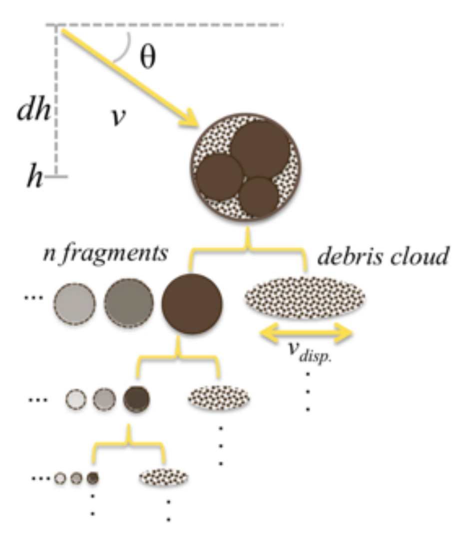
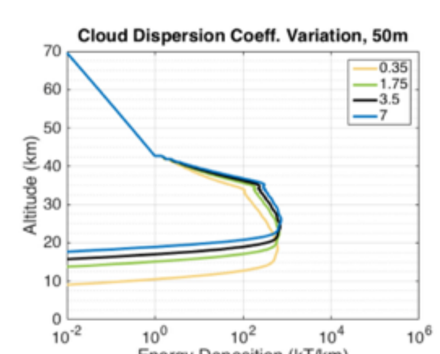


Illustration of the Fragment-Cloud Model (FCM) [1]

$$v_{disp.} = v\sqrt{C_{disp}\rho_A/\rho_m}$$

- Uncertainty in this parameter can influence the predicted height of burst for airburst-class events

The goal of the current work is to couple a unique testing capability with state-of-the-art high-fidelity simulation tools to develop new models for asteroid fragment spreading rate

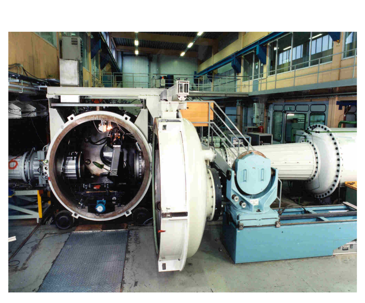


Sensitivity of energy deposition profiles to dispersion coefficient [1]

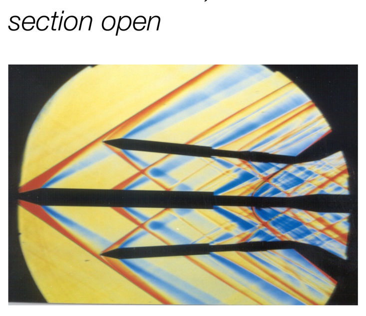
Hypersonic Wind Tunnel in Köln: *H2K*

This effort is enabled through collaboration with DLR’s H2K wind tunnel facility in Köln, Germany. The H2K facility has been used extensively to study the following:

- Free flight technique
- Static and dynamic stability
- Laminar and transitional heat fluxes
- Local aerothermodynamics
- Stage separation



H2K wind tunnel, with test section open

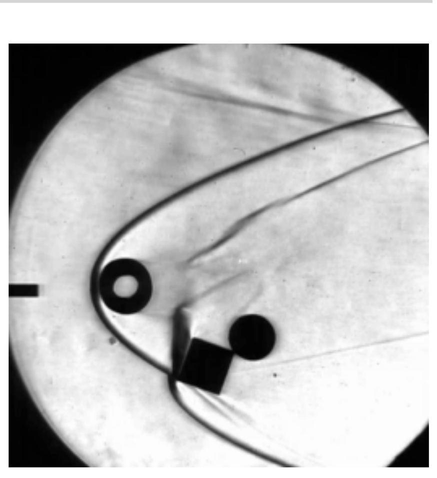


Schlieren flow-visualization of booster separation

Facility Attributes	
Mach Numbers	5.3, 6.0, 7.0, 8.7, 11.2
Reynolds Numbers	2 to 20x10⁶ [/m]
Test Section Area	60cm
Total Pressure	2.5 to 55 bar
Total Temperature	1100 K (*max*)
Typical Run Time	30s

Available Diagnostic Techniques:

- 6 components balances
- High Speed shadowgraphs and Schlieren
- Oil flow techniques
- Infrared Thermography
- Particle Image Velocimetry
- Tracking methods
- Pitot and heat flux probes

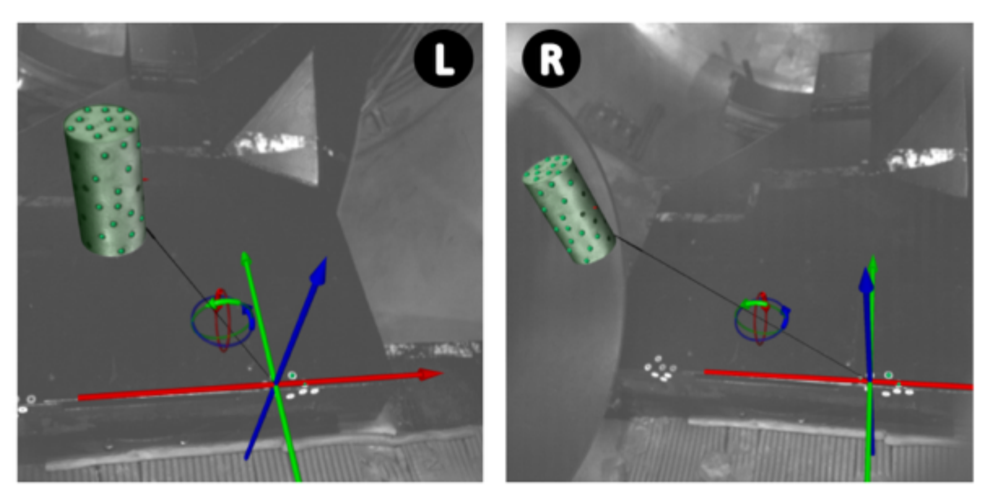


Schlieren of a cylinder, a cube, and a sphere in the free-flight wind tunnel

Experiment Diagnostics

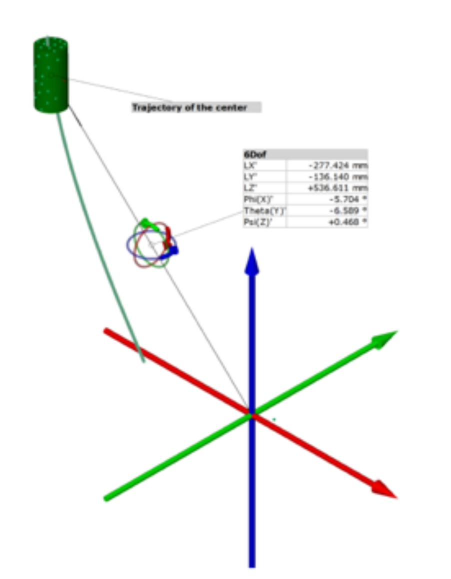
- High-speed stereo tracking with marker detection
  - Two HS-cameras: frame rates up to 12.500 fps
  - 6 DOF analysis
  - Trajectory reconstruction with commercial tool

Cylinder with tracking paint



Left and right views from the stereo tracking cameras

- Schlieren images
  - One HS-camera: frame rates up to 3500 fps
  - Visualization of flow field and shocks
- Release mechanism
  - Possibility of different body shapes, sizes, orientation and numbers

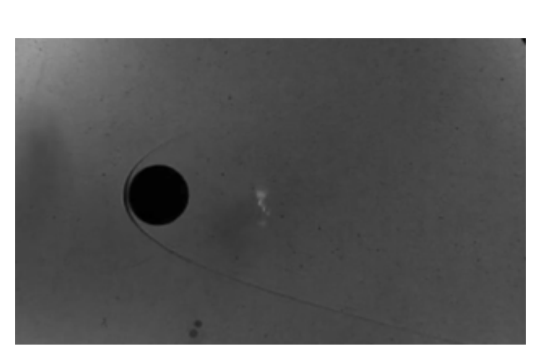


Reconstructed trajectory and attitude for a cylinder experiment

Single-sphere Validation

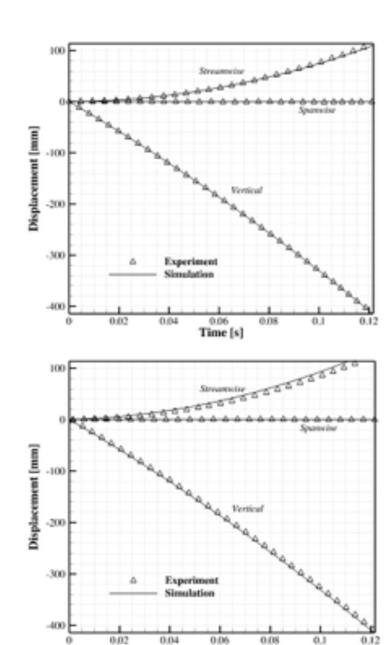
- We first seek to assess the validity of our simulation tools using experimental data of single sphere in free-flight

Run	Mach	Velocity [m/s]	Reynolds Number [x10⁶ /m]
1	7.0	1045.94	2.12
2	7.0	1169.21	1.70
3	7.0	916.04	3.57



Schlieren of single sphere in free-flight

- Simulation results show good agreement with data from experiment
- Some discrepancy observed for high Reynolds number case

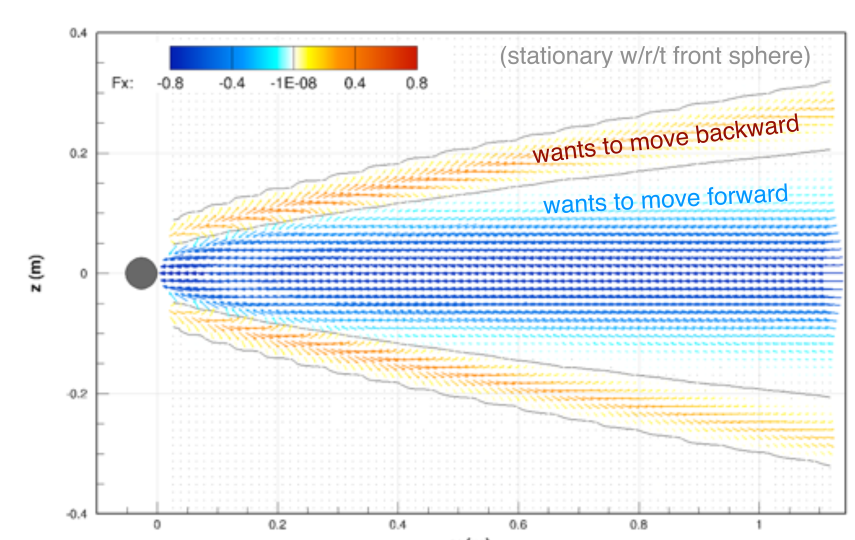


Comparison of predicted displacements to experiment for runs 1 (top) and 3 (bottom)

Database Approach to Asteroid Spreading

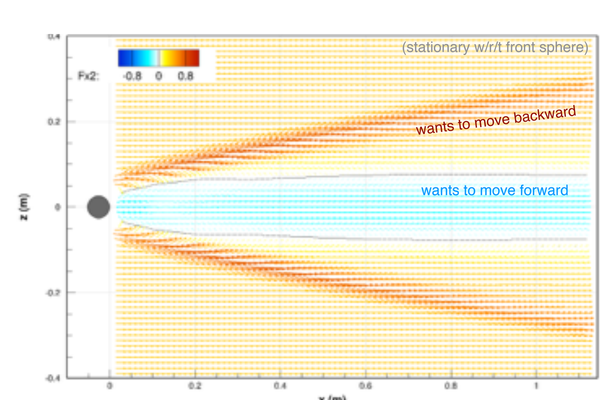
Approach to developing new fragment spreading model is to compute large aerodynamic databases for multiple bodies in free-flight, and integrate equations of motion through the database.

- Utilize the Cart3D Inviscid flow solver to compute large number of configurations of multiple spheres
  - Cart3D is highly scalable, automated mesh refinement, enabling the quick generation of large aerodynamic databases



Visualization of the relative force coefficient vectors from a database calculation (3485 simulations) for two equally sized spheres

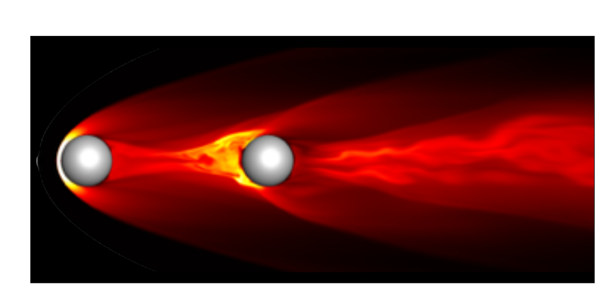
- Database allows us to visualize the directions that a second sphere will move, depending on where it is placed relative to the leading sphere
- Maximum spreading velocity observed when second sphere is in the oblique shock of the first sphere
- When a smaller second sphere is considered, there is a greater tendency for them to move apart



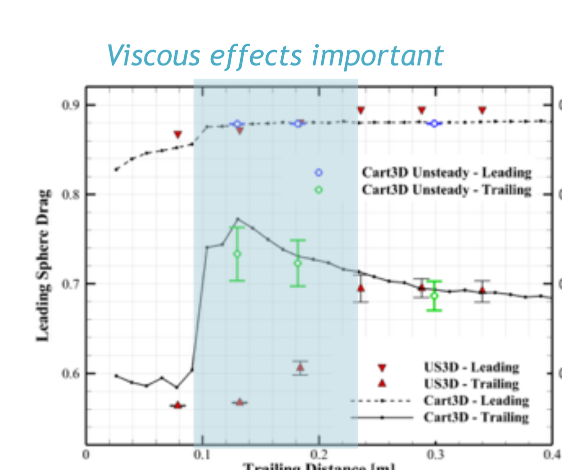
Visualization of the relative force coefficient vectors when the trailing sphere is half the diameter of the leading sphere

Effect of Viscosity

- Primary flow solver, Cart3D, neglects fluid viscosity
- Outside of the wake of the leading body, this is a good assumption, however in the wake viscosity should be considered
- The US3D flow solver is utilized at discrete locations within the wake to correct the database
- Viscosity effects *reduce* drag on trailing sphere



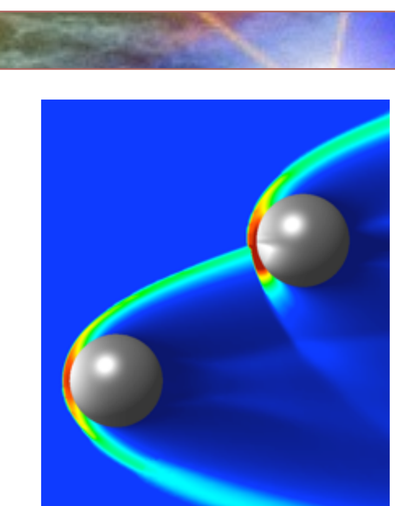
Flow visualization from unsteady US3D simulation of two spheres in free-flight



Compute drag coefficients using inviscid and viscous flow solvers

Future Work

- Utilize database to perform Monte Carlo simulations of large numbers of initial two-sphere configurations, and compute spread-rate distributions
- Extend database approach to additional shapes, and validate using data from experiments



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References:
[1] Wheeler, L. F., et al., (2017), *Icarus.* [2] Passey, Q. R., & Melosh, H. J. (1980). *Icarus.* [3] Hills, J. G., & Goda, M. P. (1993), *Astronomical Journal*.